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Addendum
Where we are on θ_{13}: addendum to 'Global neutrino data and recent reactor fluxes: status of three-flavor oscillation parameters'

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Abstract. In this addendum to Schwetz *et al* (2011 *New J. Phys.* **13** 063004), we consider the recent results from long-baseline $\nu_\mu \rightarrow \nu_e$ searches at the Tokai to Kamioka (T2K) and Main Injector Neutrino Oscillation Search (MINOS) experiments and investigate their implications for the mixing angle θ_{13} and the leptonic Dirac CP phase δ. By combining the 2.5σ indication for a nonzero value of θ_{13} coming from the T2K data with global neutrino oscillation data, we obtain a significance for $\theta_{13} > 0$ of about 3σ with best fit points $\sin^2\theta_{13} = 0.013$ (0.016) for normal (inverted) neutrino mass ordering. These results depend somewhat on assumptions concerning the analysis of reactor neutrino data.

Contents

1. Introduction

Prompted by the recently published indication for electron neutrino appearance by the T2K experiment [1], we have updated the global neutrino oscillation analysis presented in [2]. The T2K experiment uses a neutrino beam consisting mainly of muon neutrinos, produced at the J-PARC accelerator facility and observed at a distance of 295 km and an off-axis angle of 2.5° by the Super-Kamiokande detector. The present data release corresponds to 1.43×10^{20} protons on target [2]. Six events pass all selection criteria for an electron neutrino event. In a three-flavor neutrino oscillation scenario with $\theta_{13} = 0$ the expected number of such events is 1.5 ± 0.3 (syst). Under this hypothesis, the probability of observing six or more candidate events is 7×10^{-3}, equivalent to a significance of 2.5σ. We investigate the implications of this result for the mixing angle θ_{13} and the leptonic Dirac CP phase δ, focusing on long-baseline $\nu_\mu \to \nu_{\mathrm{e}}$ appearance data from T2K and MINOS in section 2, whereas the results of a combined analysis of global neutrino oscillation data are presented in section 3.

2. Long-baseline $\nu_\mu \to \nu_{\mathrm{e}}$ appearance data from T2K and MINOS

For our re-analysis of T2K, we use the spectral data shown in figure 5 of [2] given as 5 bins in reconstructed neutrino energy from 0 to 1.25 GeV. Using the neutrino fluxes predicted at Super-Kamiokande in the absence of oscillations provided in figure 1 of [2], we calculate the $\nu_\mu \to \nu_e$ appearance signal by tuning our prediction to the corresponding prediction in figure 5 of [2]. In the fit we include the background distribution shown in that figure with a systematic normalization uncertainty of 23% and adopt the χ^2 definition based on the Poisson distribution. The calculation is performed by using the GLoBES simulation software [3]. Latest MINOS data on the $\nu_\mu \to \nu_e$ channel have been presented in [4], corresponding to 8.2×10^{20} protons on target, compared to the 7×10^{20} used in [1]. MINOS finds 62 events with an expectation in the absence of oscillations of $49.6 \pm 7.0(\text{stat}) \pm 2.7(\text{syst})$, showing no significant indication for $\nu_\mu \to \nu_e$ transitions.

In figure 1, we show the region in the $\sin^2\theta_{13} - \delta$ plane indicated by T2K data in comparison to MINOS results. Whereas for T2K we obtain a closed region for $\sin^2\theta_{13}$ at 90% CL ($\Delta\chi^2 = 2.7$), for MINOS we found only an upper bound. As is clear from the figure, T2K and MINOS results are compatible with each other and we show the combined analysis as shaded regions, where the upper bound is determined by the MINOS constraint while the lower bound is given by T2K. Best fit values are in the range $\sin^2\theta_{13} \approx 0.015$–$0.023$, depending on the CP phase δ, where the variation is somewhat larger for the inverted mass hierarchy. The dotted lines in this figure indicate the 90% CL upper bound on $\sin^2\theta_{13}$ coming from a combined analysis of the remaining oscillation data, including global reactor, solar, atmospheric and long-baseline disappearance data.

3. Global analysis

We move now to the combined analysis of the T2K and MINOS ν_e appearance searches with global neutrino oscillation data as described and referenced in [1]. For the reactor analysis we use the 'recommended' analysis from [1], which adopts the new reactor neutrino fluxes from [5] while including short-baseline reactor neutrino experiments with baselines $\lesssim$100 km in the fit. The results for θ_{13} are summarized in figure 2. For both neutrino mass hierarchies we found that

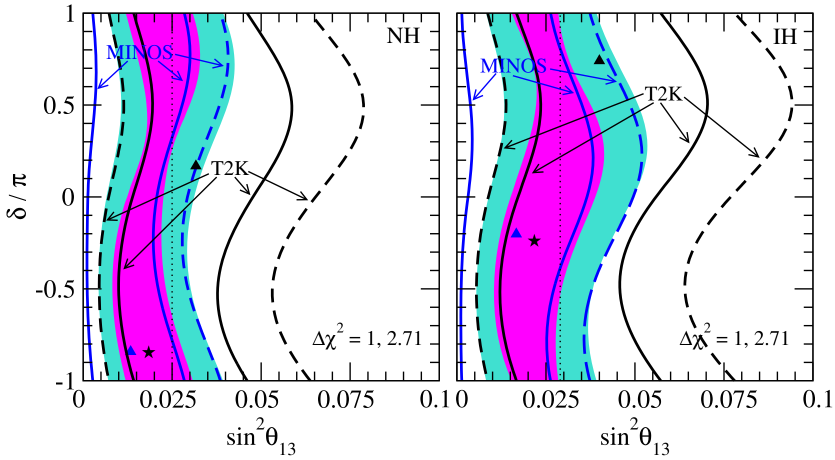

Figure 1. Contours of $\Delta\chi^2 = 1$, 2.71 for T2K and MINOS appearance data (curves) and their combination (shaded regions). For all other oscillation parameters we assume best fit values and uncertainties according to table 1, and we include a 5% uncertainty on the matter density. The left (right) panel is for normal (inverted) mass hierarchy. The dotted line shows the 90% CL upper limit on $\sin^2\theta_{13}$ from a combined analysis of all other oscillation data. The blue (black) triangle corresponds to the best fit point of the MINOS (T2K) data analysis, while the black star denotes the best fit point of the combined MINOS + T2K analysis.

the 2.5σ indication for $\theta_{13} > 0$ from T2K gets pushed to the 3σ level ($\Delta\chi^2 = 9$) when combined with the weak hint for a nonzero θ_{13} obtained from the remaining data [1]; see also [6]. We found best fit points at

$$\begin{aligned} \sin^2\theta_{13} &= 0.013, \quad \delta = -0.61\pi \quad \text{(normal hierarchy)}, \\ \sin^2\theta_{13} &= 0.016, \quad \delta = -0.41\pi \quad \text{(inverted hierarchy)}. \end{aligned} \tag{1}$$

Due to some complementarity between T2K and MINOS, one obtains, after combining with the θ_{13} limit from the rest of the data, a 'preferred region' for the CP phase δ at $\Delta\chi^2 = 1$, as seen in figure 2. Obviously this preference for the CP phase is not significant[3]. Marginalizing over the CP phase δ (and all other oscillation parameters) we obtain for the best fit, one-sigma errors, and the significance for $\theta_{13} > 0$:

$$\begin{aligned} \sin^2\theta_{13} &= 0.013^{+0.007}_{-0.005}, \quad \Delta\chi^2 = 10.1\ (3.2\sigma) \quad \text{(normal)}, \\ \sin^2\theta_{13} &= 0.016^{+0.008}_{-0.006}, \quad \Delta\chi^2 = 10.1\ (3.2\sigma) \quad \text{(inverted)}. \end{aligned} \tag{2}$$

As expected the upper bound on $\sin^2\theta_{13}$ is dominated by global data without long-baseline appearance data, whereas the lower bound comes mainly from T2K.

Let us briefly consider the sensitivity of these results to the assumptions on the analysis of reactor neutrino data. As discussed in detail in [1], there is a slight tension between reactor neutrino fluxes obtained in [5] and the results of short-baseline reactor neutrino experiments with baselines $\lesssim$100 km. The increase of reactor neutrino fluxes compared to previous calculations in [5] has been confirmed qualitatively by an independent recent calculation [8].

[3] Prospects to constrain δ with the present generation of experiments have been discussed in [7].

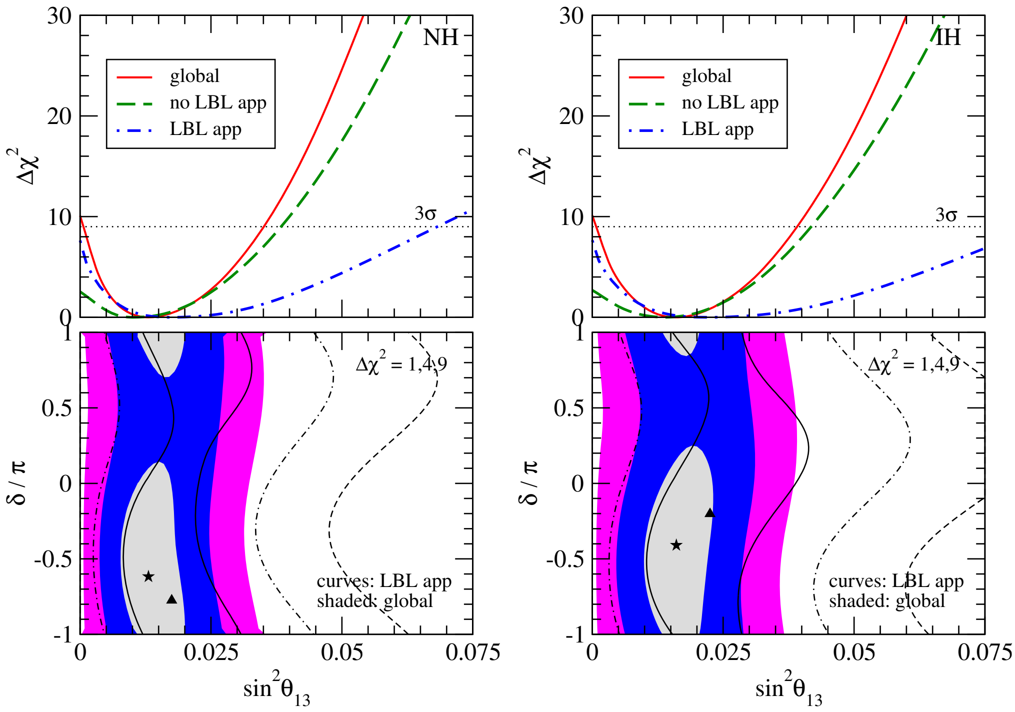

Figure 2. Upper panels: $\Delta\chi^2$ as a function of $\sin^2\theta_{13}$ for T2K and MINOS ν_e appearance data ('LBL app'), all the other global data ('no LBL app') and the combined global data ('global'). Lower panels: contours of $\Delta\chi^2 = 1, 4, 9$ in the $\sin^2\theta_{13} - \delta$ plane for LBL app (curves) and for the global data (shaded regions). We minimize over all undisplayed oscillation parameters. Left (right) panels are for normal (inverted) neutrino mass hierarchy. The triangle (star) corresponds to the best fit point of the LBL app (global) analysis.

To illustrate the impact on θ_{13}, we show the results for two alternative assumptions for the reactor analysis. Adopting the fluxes from [5] but omitting reactor experiments with baselines $\lesssim$100 km, we obtain for the best fit, one-sigma errors, and the significance for $\theta_{13} > 0$:

$$\begin{aligned} \sin^2\theta_{13} &= 0.022 \pm 0.008, \quad \Delta\chi^2 = 13.5\,(3.7\sigma) \quad (\text{NH}) \\ \sin^2\theta_{13} &= 0.026 \pm 0.009, \quad \Delta\chi^2 = 15.2\,(3.9\sigma) \quad (\text{IH}) \end{aligned} \quad (\text{no SBL react}). \tag{3}$$

If instead we do include the short-baseline reactor data but leave the overall normalization of the reactor neutrino flux free, we obtain

$$\begin{aligned} \sin^2\theta_{13} &= 0.011^{+0.007}_{-0.004}, \quad \Delta\chi^2 = 7.7\,(2.8\sigma) \quad (\text{NH}) \\ \sin^2\theta_{13} &= 0.014^{+0.007}_{-0.006}, \quad \Delta\chi^2 = 8.4\,(2.9\sigma) \quad (\text{IH}) \end{aligned} \quad (\text{flux free}). \tag{4}$$

We see that the precise value of the $\sin^2\theta_{13}$ best fit point, as well as the significance for $\theta_{13} > 0$, still depend on assumptions on the reactor analysis, as discussed in detail in [1].

To summarize, we display the status for all neutrino oscillation parameters from the global analysis using the default reactor treatment in table 1. If θ_{13} is indeed within the currently indicated range, we may expect a confirmation by future T2K data soon. Depending on whether its true value is close to the upper of the lower edge of the currently favored range, an independent confirmation of a nonzero θ_{13} may be expected from reactor

Table 1. Summary of neutrino oscillation parameters. For Δm^2_{31}, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$ and δ, the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. See [1] for details and references therein.

Parameter	Best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} (10^{-5} eV^2)	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} (10^{-3} eV^2)	$2.50^{+0.09}_{-0.16}$	2.25–2.68	2.14–2.76
	$-(2.40^{+0.08}_{-0.09})$	−(2.23–2.58)	−(2.13–2.67)
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$	0.41–0.61	0.39–0.64
	0.52 ± 0.06	0.42–0.61	
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$	0.004–0.028	0.001–0.035
	$0.016^{+0.008}_{-0.006}$	0.005–0.031	0.001–0.039
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$	0–2π	0–2π
	$\left(-0.41^{+0.65}_{-0.70}\right)\pi$		

experiments within a few months to a few years [9]. After establishing the large mixing angle-Mikheyev–Smirnov–Wolfenstein (LMA-MSW) solution to the solar neutrino problem, the present 3σ indication for a nonzero θ_{13} may turn out to be the first sign of the second necessary ingredient for observable CP violation in neutrino oscillations; see, e.g., [10] for a review.

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